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THIRD-GENERATION STRUCTURES: INTELLIGENT HIGH-PERFORMANCE STRUCTURES FOR SUSTAINABLE URBAN SYSTEMS

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ABSTRACT: Ancient structures, which are herein referred to as first-generation structures, were built with natural materials such as stones, bricks and timbers. Steel and concrete, which are man-made, provided the revolution needed for modern structures (i.e. second-generation structures) to cater for the infrastructure demands generated by rapid economic growths, particularly following World War II. Extensive research is now under way around the world to develop advanced technologies to enhance the performance of structures. While these technological advances are incremental in nature, they will eventually lead to structures which are distinctly different from second-generation structures. These new structures are therefore referred to as third-generation structures. This paper aims to define the features and benefits of third-generation structures and the technological basis for such structures. Current and future research that will provide this technological basis is also discussed, and where appropriate brief reference is made to work being undertaken at The Hong Kong Polytechnic University where the ideas presented in this paper have been collectively formulated under the leadership of the second author.

KEYWORDS: third-generation structures, intelligent structures, high performance structures, sustainable development.

1. INTRODUCTION

The 20th century witnessed urbanization of the world's population on a massive scale, leading to the development of mega-cities around the world. This trend is expected to continue in the 21st century, particularly in Asia due to its high population density. Hong Kong is a good example of modern mega-cities, where a population of nearly 7 million live on a small area of 1098 square kilometres.

The smooth functioning of a modern large city depends on the reliability of many inter-linked systems which all have to be designed, constructed, monitored and maintained over a long period of time. Among these systems is the large number of structures, including buildings and bridges, which often comprise the major part of the infrastructure investment in a city. This paper presents ideas regarding the development of a new generation of structures (i.e. referred to as third-generation structures) which will better support the development of sustainable urban systems. The paper aims to define the features and benefits of third-generation structures and the technological basis for such structures. Current and future research that will provide this technological basis is also discussed, and where appropriate brief reference is made to work being undertaken at The Hong Kong Polytechnic University where the ideas presented in this paper have been collectively formulated under the leadership of the second author. It should be noted that while explicit reference to dense urban environments is often made in the paper, many of the issues discussed here are also applicable to structures in non-urban areas.

2. THIRD-GENERATION STRUCTURES

Over the long human history, structures have evolved in both their form and the materials used to construct them. They may thus be classified into three generations based on the technologies employed as detailed below.

Pre-modern structures were built with natural materials such as stones, bricks, timbers and bamboos. The preference for a particular material to the others was often dictated by factors including local availability, natural environments and cultural considerations. The Great Wall, the Zhaozhou Stone Arch Bridge and the Pagodas in China are good examples of these structures. In addition to the use of natural materials, another aspect of these structures is that they were in general not engineered using modern scientific principles. These structures are thus referred to in this paper as first-generation structures.

Steel and concrete, the two man-made materials which have been used to construct structures since the latter half of the nineteenth century, still remain as the two primary construction materials today. They provided the revolution needed for modern structures to cater for the infrastructure demands generated by rapid economic developments, particularly following World War II. These modern steel and concrete structures are referred to as second-generation structures. They are characterised by the use of high-strength man-made materials and engineering designs based on modern scientific principles. Over the 20th century, many advances have been made in technologies for the design and construction of structures. The main aim of these advances has been to enable the construction of structures of greater spans and heights, and with greater safety and less cost.

The second-generation structures, while able to offer strength and stiffness, have suffered from many problems including deterioration far beyond that initially expected, inability to respond adaptively to extreme loadings, and irrationality and inflexibility in design methods. All these problems are rooted in the traditional and widespread belief that the structural engineer’s job is done once the structure is built with a certain assumed service life. This belief has been questioned increasingly more frequently over recent decades, as problems with second-generation structures are better understood. It is now quite widely realised that the structural engineer should be responsible not only for the design of a structure, but also for ensuring a healthy life of the structure and prolonging its life span whenever required. Here, a good analogy can be drawn between the doctor-patient relationship and the engineer-structure relationship. The engineer needs to vaccinate the structure to provide immunity from severe attacks (control), check the health of the structure regularly particularly when it is in its old age (monitoring), determine the cause of any problem (diagnosis), prescribe the necessary remedial measures (rehabilitation), and allow a longer service life when possible.

The above life-long approach to structural health requires the development of a new integrated technological basis for future structures which are referred to as third-generation structures. Currently, solid progresses are being made around the world on a number of fronts for the development of this technological basis, exploiting recent technological advances in various disciplines including material, sensor, control, information, communication and measurement technologies. It may be fair to say that the time has come for researchers to harness these advances through amalgamation, adaptation and further development to create an integrated technological basis for the design and construction of third generation structures.

Based on the above discussions, future third-generation structures may be expected to possess the following salient features:

(a) durable in the sense that they are highly resistant to environmental degradation over time;

(b) intelligent, in the sense that they are able to continuously monitor their own state of health and activate the control devices when necessary to minimise the effects of extreme loadings (e.g. strong winds, earthquakes, fires and land slides) to ensure desirable structural performance; and

(c) performance-oriented, in the sense that they are designed and constructed to satisfy specific whole-life system-level performance objectives.

Table 1 summarizes the key differences between the three generations of structures. It is clear that the second-generation represents advances over the first generation in both the materials and design methods, but the third generation represents advances also in the additional area of "intelligence".

Table 1: Differences between the three generations of structures

Structural generation	Materials	Design technology	Intelligence
First	Naturally occurring materials	Experience-based	None
Second	Man-made materials such as steel and concrete	Engineering design to ensure code-prescribed safety and serviceability criteria	None
Third	High performance man-made materials such as polymer and cementitious composites in combination with traditional man-made materials	Engineering design to achieve client-specified system-level performance objectives in a flexible manner	Intelligent monitoring and control based on information and smart materials technologies

3. BENEFITS OF THIRD-GENERATION TECHNOLOGIES

For large structures such as tall buildings and long-span bridges in a dense urban environment, third-generation structures possess a number of major advantages over second-generation structures. In this section, their advantages in four areas are discussed with particular reference to Hong Kong, but these advantages are equally available to other similar urban centres.

Hong Kong is a densely-populated, large urban centre with a corrosive coastal environment. Hong Kong is also among the most active typhoon regions in the world with the estimated probability of being directly hit by a typhoon with an hourly mean wind speed of 32m/s being no less than once in 10 years. Furthermore, Hong Kong is a seismically active area as classified by the China Seismological Bureau, with a design peak ground acceleration of 0.15g at the bedrock for a return period of 475 years. Given these environments in which structures have to perform, the advantages of third-generation structures mean great economic benefits for Hong Kong.

3.1 DURABILITY

Steel and concrete, when first deployed as construction materials, were believed to be long lasting. However, deterioration has occurred in many structures to a degree far beyond that expected at the time of design, with the most obvious being corrosion of steel reinforcement in concrete structures. Corrosion problems are most prevalent in concrete structures at sea fronts, in environments which are humid and hot, or subject to extensive use of de-icing salts or direct chemical attacks. As an example, it was reported in a recent paper (Tang and Hooks 2001) that in the United States, more than 173,000 of the total of over 583,000 bridges had been classified as either functionally obsolete or structurally deficient and the cost for restoring these bridges was estimated to be US$87 billion. In Canada, the deteriorating infrastructure needs 49 billion Canadian dollars for rehabilitation as reported recently in a paper by the President of ISIS Canada (Mufti 2001) which has an extensive nation-wide program on the research and application of FRP composites and intelligent sensing. The deterioration problem is of similar severity in other developed areas of the world such as Europe. Hong Kong and China as a whole are already facing large deterioration problems although most of their structures are of a comparatively young age, and these problems will grow rapidly as the infrastructure ages. The rehabilitation cost apart, deterioration has also been the cause of many tragic structural failures. With the fast growth of China's economy, many meg-scale infrastructure projects will be carried out in the future. If Hong Kong and China as a whole are to avoid the deterioration problem now faced by the developed countries in the future, the development of durable third-generation structures is essential.

3.2 INTELLIGENCE

Despite many efforts and improvements, second-generation structures fail on a large scale during earthquakes, strong winds and fires. Recent examples include the Northridge earthquake in 1994, the

Kobe earthquake in 1995, the Chi-chi earthquake in Taiwan in 1999, Hurricane Andrew in Florida in 1992 and the fire at the Word Trade Centre Towers in New York in 2001. Each event caused the loss of many lives and damages of billions of US dollars. The poor performance of second-generation structures under severe hazards, among other things such as deterioration, can be attributed to the unpredictability of these hazards. The problem can only be completely solved if the structure is able to sense the severity of the attack, know its own resistance, and respond adaptively by activating control devices not in use in normal times. Third-generation structures shall have the intelligence to deal with the unpredictability of severe natural and man-made hazards, thereby greatly enhancing structural safety at the smallest cost through performance-based design and monitoring. The benefit is thus enormous.

3.3 COST-EFFECTIVE STRUCTURES WITH DESIRED PERFORMANCE

Second-generation structures are generally designed on the basis of linear elastic analysis for member forces and member design for serviceability and ultimate limit states, although in a few cases performance assessment of the structure following design is carried out. This design approach is generally conservative, leading to more expensive structures, but can often be unsafe particularly when subject to severe hazards with unpredictability such as earthquakes. This is because the real performance of the structure is never predicted during design, as there is often a gulf between member behaviour and system behaviour. The designs are also rigidly limited to code-specified criteria, so an optimal balance between performance and cost, as requested by a client to achieve the most effective solution, is not possible. These restrictions and disadvantages can be overcome by the development of the performance-based design approach for third-generation structures. Within this approach, there is the possibility to employ different techniques to achieve various levels of performance objectives as specified by the client for a given life span, with an optimal compromise between performance and cost. The performance-based approach provides the appropriate framework for the integration of sensing, monitoring and control functions into third-generation structures, as the state of the structure has to be judged in all cases in terms of system-level performance.

3.4 FOUNDATIONS ON DIFFICULT SITES

In third-generation structures, both the super structure and the foundation shall possess the above three features of durability, intelligence and performance-based design. For a dense urban environment like Hong Kong where it is common to construct structures on sloping or soft soil sites (old or newly reclaimed land on the seabed), third-generation foundations offer special benefits.

For structures on slopes, the stability of slopes is of great importance, but accurate predictions of the movements and failure of a slope are extremely difficult due to uncertainty in many aspects including subsurface conditions and soil/rock properties. Similarly, the behaviour of pile foundations installed in soft soils is often difficult to predict accurately. The quality of pile construction is another great concern. Furthermore, conventional technologies suffer from a number of critical limitations for the monitoring of foundations on slopes and soft soil sites. In third-generation structures, with an intelligent foundation system, foundation-related-problems such as short pile lengths, excessive settlements, and damage due to landslides can be minimised and remedied.

4. TECHNOLOGICAL BASIS FOR THIRD-GENERATION STRUCTURES

Figure 1 shows how different advanced technologies may be amalgamated into an integrated technological basis for the design and construction of third-generation structures. While the basic technological inputs come from different disciplines, they can be broadly grouped into two categories: (a) material technologies; and (b) information and related technologies. A number of technological areas in which civil/structural research engineering is being undertaken, each rooted in one of the two or both categories, are identified by shaded boxes in Figure 1. In the following sections, research issues for the development of third-generation structures are discussed area by area in some detail, and where appropriate, reference is made to work being undertaken at The Hong Kong Polytechnic University.

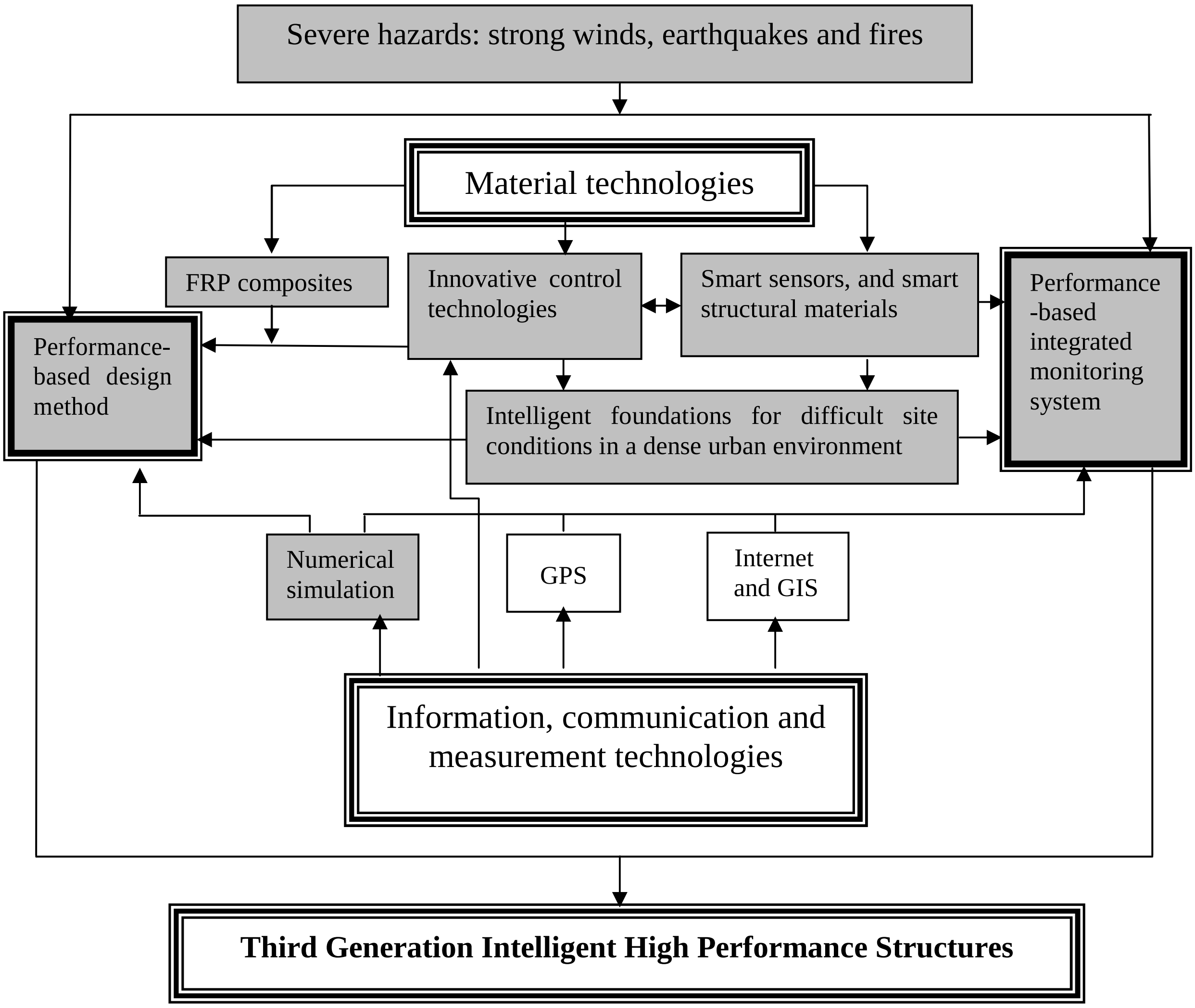

Figure 1. Technological Basis for Third-Generation Structures

5. NATURES AND EFFECTS OF SEVERE HAZARDS INCLUDING STRONG WINDS, EARTHQUAKES AND FIRES

For the development of third-generation structures, the use of more sophisticated design methods demand a better understanding of the natures and effects of severe hazards including strong winds, earthquakes and fires. Here, the use of advanced computational tools, in conjunction with full-scale measurements (e.g. Xu and Zhan 2001), should be particularly useful. For example, the development and application of computational fluid dynamics models to predict wind loading has received a great deal of recent attention and has the promise of accurate predictions of wind loading and wind-structure interactions. In such studies, issues of special importance to large urban centres such as the close spacing of buildings and the boundary wind structures over an urban area should be given particular attention.

Computational fluid dynamics can also be employed to develop numerical models for fire loadings on structures for integration with a numerical model for structural performance. This will allow the simulation of the effect of spread of fire on the safety of a structure since the collapse analysis under fire can be based on the temperatures of the structural elements at various times.

The reliability of seismic design of buildings depends strongly on an accurate estimation of seismic hazard levels. Further research is needed to develop better methods for seismological and geotechnical characterizations of ground motions in dense urban areas, with particular attention to topographical effects.

6. FRP COMPOSITES FOR DURABLE STRUCTURES

FRP (fibre-reinforced polymer) composites are formed by embedding continuous fibres in a resin matrix which binds the fibres together. Common fibres include carbon, glass, and aramid fibres while common resins are epoxy, polyester, and vinyl ester resins. The most widely used FRP composites are glass FRP (GFRP) composites, carbon FRP (CFRP) composites, and aramid FRP (AFRP) composites. FRP composites are a new generation of structural materials for civil engineering structures. They are light, strong and highly corrosion resistant. Due to these advantages, they offer great opportunities for the retrofit of existing structures and for constructing high-performance third-generation structures. Although the retrofit of existing structures is not strictly an integral part of the technological basis of third-generation structures, the topic is also briefly covered below to provide the appropriate background for the application of FRP composites in civil engineering.

6.1 FRP RETROFIT OF STRUCTURES

Over the last few years, external bonding/wrapping of FRP composites has become a very popular method for the strengthening of deficient reinforced concrete (RC) structures, due to the many advantages of FRP composites. Taking savings in labour and maintenance costs into account, FRP bonding/wrapping has been found to be the most cost effective solution in many strengthening projects (Hollaway and Leeming 1999). The external bonding/wrapping of FRP composites to RC structures leads to a new structural system which displays a number of unique failure modes and modifies some well known failure modes of conventional RC structures. Consequently, extensive research has been carried out on FRP-strengthened RC structures around the world. At The Hong Kong Polytechnic University, a strong research program has been going on in this area, with emphasis on understanding the failure mechanisms and developing rational strength models. The research has covered many different problems (e.g. Lam and Teng 2001; Smith and Teng 2002; Teng and Lam 2002; Chen and Teng 2003) and has led to a recent book (Teng et al. 2002) summarizing the state-of-the-art of the existing understanding of the behaviour of FRP-strengthened RC structures. The book also identifies a large number of issues requiring further research. For a glimpse of current research activities in this area around the world, the reader may also refer to the proceedings of recent international conferences such as Burgoyne (2001) and Teng (2001).

6.2 FRP FOR NEW STRUCTURES

The high strength-to-weight ratio and corrosion resistance of FRP composites make them an important construction material for third-generation structures. The appropriate use of FRP composites can eliminate the steel corrosion problem and thus greatly enhance the durability of civil engineering structures. Research is currently underway around the world to develop a variety of applications of FRP composites in new construction which will offer innovative and durable solutions for third-generation structures. The topics being investigated include FRP reinforcing bars and prestressing tendons for concrete structures; hybrid FRP structures with innovative combination of FRP and other materials; and all FRP structures such as FRP bridge decks and FRP cables in cable-stayed bridges and roofs. New structural forms and new or improved analysis and design approaches are expected to emerge from this research. FRP composites are particularly suitable for integration with fibre optical sensors as they can be easily embedded and thus protected by the matrix of FRP composites. Integration of fibre optic sensors into FRP will lead to intelligent FRP structures. At The Hong Kong Polytechnic University, research on the development of new structural forms featuring optimal combination of FRP, steel, concrete and intelligent sensing has recently commenced and is expected to produce important results in the near future. For example, a new form of hybrid FRP-concrete-steel double skin (FCSDS) columns has recently been proposed (Teng 2003). The column consists of an outer FRP tube, an inner steel tube and concrete in the annular space between the two tubes. Figure 1 shows such columns after failure under axial compression. These columns are expected to offer many advantages over existing concrete-filled steel or FRP tubes, including light weight, high stiffness, high strength and high durability.

Figure 2. Innovative hybrid FRP-concrete-steel double skin columns

7. SMART SENSORS AND SMART STRUCTURAL MATERIALS

Smart sensors are expected to be an important ingredient of third-generation structures. Candidate smart sensors for structural applications include optical fibre-based sensors, ferro-magnetic sensors, shape memory alloys and piezoelectric sensors. As sensor technologies advance, periodical evaluations of their performance should be conducted to identify the best-performing sensors available for the measurement of structural responses (e.g. displacement, velocity, acceleration, strain, and stress) and detecting structural damage (e.g. cracking, fatigue and corrosion). Such evaluations should consider their performance (e.g. reliability, sensitivity, integrity, and robustness) not only as stand-alone sensors but more importantly when externally attached to structural members as well as internally embedded in concrete and FRP materials.

Among the various smart sensors, optical fibre sensors have no doubt been the most popular in the monitoring of civil engineering structures. They have been extensively employed as real-time health monitoring tools in advanced aircraft and space vehicles (Friebele et al. 1999). Optical fibre sensors have several inherent advantages over conventional electrical sensors such as their small size, light weight, non-conductivity, fast response, resistance to corrosion, higher temperature capability, and immunity to electromagnetic noise and ratio frequency interferences (Schulz et al. 1998; Sun et al. 1999). Their multiplexing capability makes it practical to undertake distributed sensing and measurements within a structure. These sensors can be attached to the surface of or embedded into structural elements to continuously monitor conditions. Another attractive feature of optical fibre sensors is their inherent ability to serve as both the sensing element and the signal transmission medium which opens new possibilities in the field of reliable remote structural monitoring.

Despite the extensive use of optical fibre sensors in the aeronautical industry, the technologies developed there cannot be directly employed in the condition monitoring of civil engineering structures (Ansari 1998). Full adaptation of the optical fibre sensor technology to civil engineering structures requires multi-disciplinary research among civil engineers, optical experts and material scientists. At The Hong Kong Polytechnic University, a research team comprising members from the Department of Civil and Structural Engineering and the Department of Electrical Engineering has been formed to provide the required synergy for fundamental advances and technological developments. Work is currently under way for the installation of FBG sensor systems (Figure 3) on Tsing Ma Bridge in Hong Kong to demonstrate the capability of such systems in the distributed monitoring of civil engineering structures.

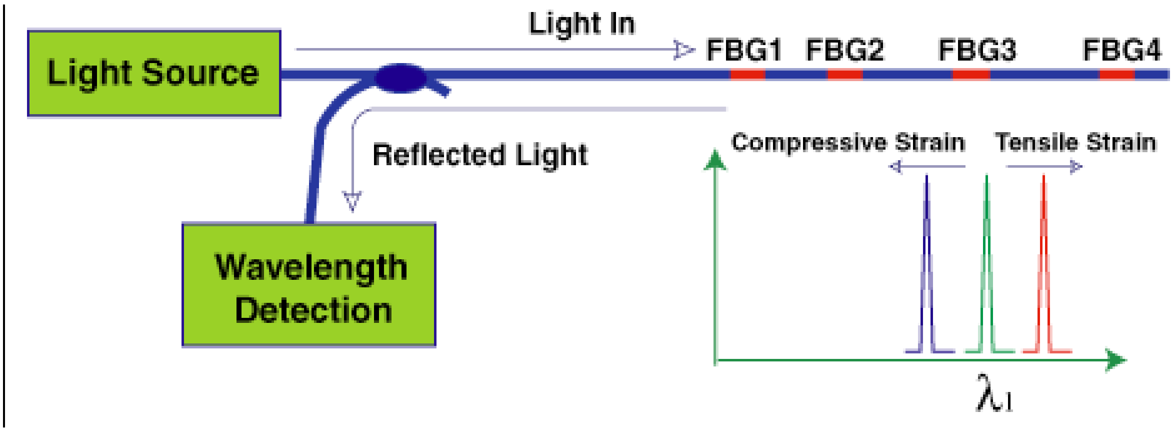

Figure 3. Principle of Fibre Bragg Grating (FBG) Sensors

8. INNOVATIVE CONTROL TECHNOLOGIES INCLUDING PASSIVE, SEMI-ACTIVE AND ACTIVE DAMPING DEVICES

Structural vibration control is to implement energy dissipation devices or control systems into structures to reduce excessive structural vibration, increase human comfort, and prevent catastrophic structural failure due to strong winds and earthquakes. Structural vibration control can also be used for the retrofit of historic buildings and structures against strong winds and earthquakes. Shape memory alloys, electro- and magneto-rheologic fluids, piezoelectric and magnetostrictive materials are candidates for intelligent control devices for large civil engineering structures to reduce the effects of extreme loadings from severe hazards. In this area, the development and performance evaluation of intelligent control systems which properly integrate sensors, control devices, control algorithms, high performance computers and other auxiliary parts, form an important research topic.

Structural vibration control has been an active research area at The Hong Kong Polytechnic University for many years where systematic investigations have been carried out on passive, semi-active, hybrid, and active control devices for a variety of structures. The Hong Kong Polytechnic University has also been involved in practical applications of this advanced technology, such as the vibration control of the Hefei Jade Tower with a height of 339 meters (the highest steel television tower in China) and the Dongting Lake Bridge.

At The Hong Kong Polytechnic University, research on passive fluid dampers has been concerned with the dynamic characteristics and seismic response of adjacent buildings linked by fluid dampers (Yang et al. 2003; Zhang and Xu 2000); the control of wind-induced vibration of the Hefei Jade Tower (Qu et al. 2001); Research has also been carried out on the possibility of incorporating passive friction dampers and semiactive friction dampers into wind-excited large truss towers to abate excessive vibration (Xu et al. 2001). In the semi-active friction dampers, piezoelectric materials are used to control the clamping force so as to regulate the slip force of the damper through simple feedback of damper motion status. Research has also been carried out on the optimal placement and optimal parameters of control devices using the linear quadratic performance index as an objective function (Xu and Teng 2002).

Researchers at The Hong Kong Polytechnic University have been active in theoretical and experimental research on smart vibration control using electro-rheological (ER) or magneto-rheological (MR) dampers (Ko et al. 2002a; Ni et al. 2002a, 2002b, 2002c). This research has resulted in the implementation of MR dampers to the cable-stayed Dongting Lake Bridge for cable vibration control. This is the world's first practical application of the MR-based smart damping technology in bridge structures. As a joint research project of The Hong Kong Polytechnic University, Central South University (China) and the University of Illinois at Urbana-Champaign (USA), a total of 312 semi-active MR dampers were installed on this bridge for wind-rain-induced vibration control of stay cables in May 2002. In another project carried out with its background being the Three-Gorge Dam project in China, the Seismic response control of large span machinery building on top of ship lift towers using

ER/MR moment controllers was studied (Qu et al. 2002). Furthermore, the possibility of using ER/MR dampers to connect the podium structure to the main building structure to prevent the whipping effect of the main building has also been explored (Qu and Xu, 2001).

Figure 4. Large scale shaking table test of adjacent buildings linked by fluid dampers

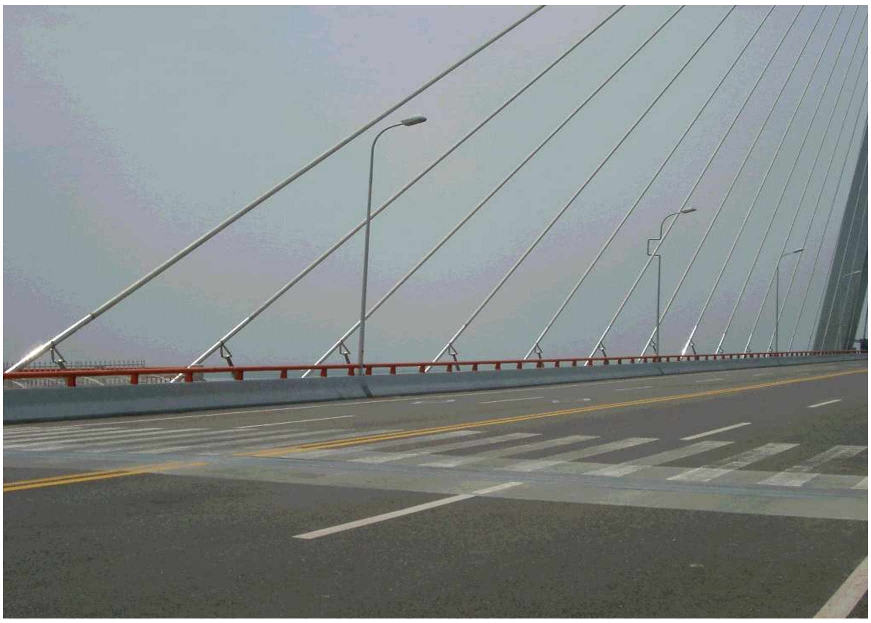

Figure 5. Wind-rain-induced vibration control of stay cables in the Dongting Lake Bridge

9. PERFORMANCE-BASED INTEGRATED MONITORING SYSTEMS WITH OPTIMALLY LOCATED SENSORS AND CONTROL DEVICES

Third-generation structures shall be equipped with an integrated monitoring system that will be able to detect structural deterioration and damage, provide early warning of structural failure, check the reliability of sensing and control systems, and activate the control system to protect the structure from extreme loadings of natural and man-made hazards. Such a system acts as the brain of the structure and involves smart sensors, GPS, GIS, wireless communication and/or the Internet technologies. The monitoring system should provide not only the state of the health of the structure but also information for the control system to make decisions with regard to its activation under extreme loadings. The GIS, especially Internet-GIS technology, provides a useful platform on which an efficient computerized spatial database management system for capture, retrieval, analysis and display of GIS data can be built.

The critical issues facing a health monitoring system for large civil engineering structures are: (i) the structure is highly redundant, (ii) the damage is localized, and (iii) detecting the location and extent of damage requires a combination of local and global measurements. Resolving these difficulties requires the development of new system identification and damage detection methods based on both local and global measurement data, together with a corresponding inspection and maintenance management plan, with an emphasis on the optimization of the locations of sensors and control devices. In particular, data from the sensors of the monitoring system shall be used to continuously update the structural model initially developed at the design stage. The predicted response from the updated model will provide more reliable information for assessing the current state and potential future condition of the structure to decide if it is fit for its purposes.

At The Hong Kong Polytechnic University, extensive research related to the long-term monitoring system WASHMS for the three cable-supported bridges in Hong Kong has been carried out. In the feasibility study stage, a neural network based hierarchical identification strategy was proposed for damage detection in accordance with the features of WASHMS. This multi-stage diagnosis strategy aims at successive detection of the occurrence, location and extent of structural damage and is more feasible than conventional procedures for damage detection of large-scale structures. After completing the feasibility study, one-year continuous data from 947 sensor channels of WASHMS has been collected to establish a database. The data has been used to develop a GIS-based health monitoring and management system. Some of this work has been reported by Ko et al. (2002b, 2003), Ni et al. (2002d, 2002e, 2003) and Wang et al. (2002).

10. ACCURATE NUMERICAL SIMULATION TOOLS FOR STRUCTURAL PERFORMANCE

Performance-based design of third-generation structures requires accurate numerical simulation tools to predict structural behaviour under various kinds and levels of loadings so that design can be carried out to achieve client-specified performance objectives with a high level of confidence. These numerical simulation tools are also required as part of the integrated monitoring system. Although the behaviour and modelling of various structural materials, components and systems have been subject to extensive research over many decades, current simulation capabilities are still far from adequate when structures are subject to complex realistic loadings. The deterioration mechanisms of various materials with time are also not yet clear.

At The Hong Kong Polytechnic University, research has been under way for many years to develop sophisticated software for the simulation of behaviour of structures under a variety of loading conditions. In particular, a powerful and user-friendly computer package for the advanced analysis of steel skeletal structures has been developed. This package has been applied to the design of various slender structures. Selected publications reporting research related to this package and its application in design include Chan and Zhou (1995, 2000), Chan and Chui (2000), and Chan and Gu (2000).

11. INTELLIGENT FOUNDATIONS FOR DIFFICULT SITE CONDITIONS IN A DENSE URBAN ENVIRONMENT

In a third-generation structure, an Internet-GIS Integrated monitoring capability for the ground and the foundation using smart sensors (e.g. optical fibres) and GPS technologies should form part of the overall integrated monitoring system so that early warning of excessive slope and foundation movements is possible and the effects of such movements on the integrity of the entire structural system can be assessed. At The Hong Kong Polytechnic University, an integrated and automatic system for slope monitoring and warning has been developed (Yin et al. 2002). This integrated system includes (a) automatic conventional instrumentation (in-place inclinometers, pore water pressure transducers, TDR, and rain gauges) and (b) a high-accuracy multi-antenna GPS package.

Research is needed to develop intelligent foundation systems for third-generation structures. The idea of isolating the superstructure from the foundation using base isolators is now well-known, but when structures are founded on piles, this base isolation strategy is difficult to implement. Figure 6 proposes and sketches a system in which the pile foundation system is separated from the superstructure. Smart and active dampers are proposed to be installed at the pile head level as well as at the base slab level. As shown in Figure 6, to avoid the effect of soil-pile structure interaction (Koo et al. 2003), which itself is an extremely complicated problem, each driven pile is proposed to be embraced in an empty casing such that no direct contact between the piles and the soil is allowed except at the base. Potential seismic pounding problems between adjacent buildings (Chau and Wei, 2001; Chau et al., 2003) can also be alleviated because of the use of such a smart isolation system. The potential horizontal loads transmitted to the piles can be taken up by the use of articulated piles. This kind of smart pile foundation system is particularly useful for the reclamation areas in Hong Kong. An actual structure which uses a similar idea for its pile foundation is the Wellington Central Police Station in Victoria Street in New Zealand completed in 1991, although none of the dampers installed were smart active dampers. This police station is in the proximity of a very active fault, which produced large earthquakes in the early twentieth century.

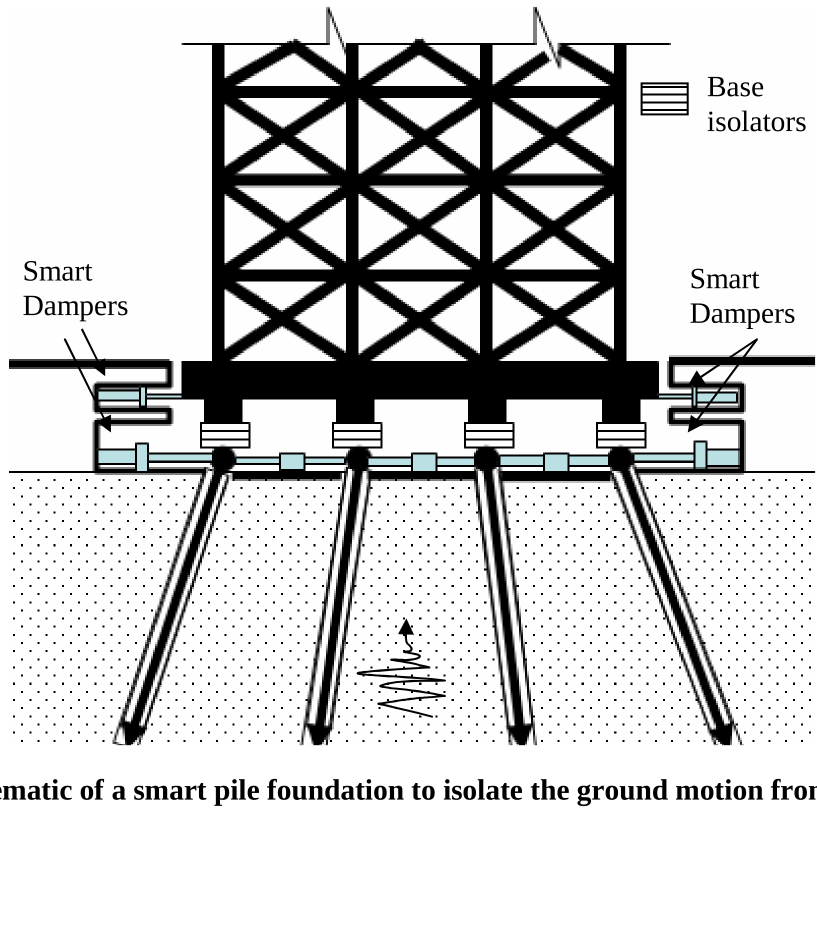

Figure 6. Schematic of a smart pile foundation to isolate the ground motion from the structure

12. WHOLE-LIFE SYSTEM-LEVEL PERFORMANCE-BASED DESIGN OF STRUCTURES

The performance-based design approach has gained popularity in the past decade in the seismic design of structures as well as other areas as a more flexible and rational design approach (Ghobarah 2001; Chandler and Lam 2001). Within this approach, there is the possibility to employ different techniques to achieve various levels of performance objectives as specified by the client for a given life span, with an optimal compromise between performance and cost. The performance-based approach provides the appropriate framework for the integration of sensing, monitoring and control functions into third-generation structures, as the state of the structure has to be judged in all cases in terms of system-level performance.

Research outlined earlier in the paper on numerical models for various loadings, numerical simulation tools for structural system behaviour, and numerical models for control systems are all important for the further development of this approach. Issues more specific to this design methodology which require further research include the definition of performance objectives of both superstructures and foundations in a dense urban environment subject to strong winds, earthquakes and fires, the appropriate acceptance criteria, the costs and benefits of achieving different levels of performance, and the necessity to differentiate between different classes of structures. This research shall be conducted with special considerations given to the conditions of a dense urban environment where the failure of a particular structure may have much greater consequences than one in a scarcely populated area.

13. CONCLUSIONS

This paper has argued that the next stage of development of structural engineering technologies will lead to a new generation of structures which may be referred to as third-generation structures, based on the classification of ancient non-engineered structures as the first generation and modern structures as the second generation. The features and benefits of third-generation structures have been defined. The main focus of the paper has been a detailed examination of various technologies which are being or should be developed that will form the backbones of the technological basis for third-generation structures.

It may be envisaged that in the era of third-generation structures, a structure will be designed using the performance-based approach employing a numerical simulation tool which can capably predict the behaviour of the structure including the contributions of control devices, the interaction between the monitoring and control mechanisms, and deterioration with time. The structure will be constructed with a powerful computer (i.e. the brain of the structure) on which an Internet-GIS based monitoring system is installed and lined to smart sensors and control devices. The behaviour of the structure, as monitored by the sensors, will be regularly compared with the predictions of the numerical model based on loadings provided by the sensors, so the computer model is continuously improved to achieve maximum accuracy. Over the life span of the structure, the state of the structure can be accurately assessed by combining the sensor inputs and the numerical model. When extreme loading conditions arise, the monitoring system will activate the control devices based on sensor inputs to protect the structure from failure. Afterwards, the monitoring system will determine the remaining life of the structure.

It will take some time before third-generation structures as envisaged above can be realised but it is hoped that in the not so distant future, the idea of third-generation structures can be implemented and studied in a number of laboratory-scale structures. Such model third-generation structures can be tested to demonstrate and assess their performance. In the transition period to the full realisation of third-generation structures, the associated technological developments can be expected to have a great impact on the performance enhancement of second-generation structures. For example, vibration control and health monitoring technologies can be implemented in existing structures for retrofit and monitoring purposes as well as in new third-generation structures. In this sense, third-generation structures and the associated technological advances offer great benefits for the sustainable development of urban systems.

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